Modeling inspiration for innovative NPD: lessons from biomimetics

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MODELING INSPIRATION FOR INNOVATIVE NPD: LESSONS FROM BIOMIMETICS

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ABSTRACT

In biomimetic design, nature – natural phenomena, systems or organisms - is used as a source of inspiration for producing new ideas or concepts. While being widely recommended this approach lacks rigorous analysis and manageable systematization that would be needed in industrial contexts. Better modeling of this process of bioinspiration is a condition for applying bioinspiration to stimulate innovation in a controlled way. This paper presents a model for bioinspiration based on the framework of the C-K design theory. This model was elaborated considering a review of the existing literature on methods for implementing biomimetic design and an analysis of selected biomimetic product development case examples. The results reveal the main roles of biological knowledge in the design process (1) indication of a "design direction", meaning an expansion on the concepts space, (2) indication of knowledge domains where no or few knowledge is available, (3) reorganization of the knowledge base, activating knowledge bases that would not otherwise be activated. This improved understanding of the bioinspiration process outlines more sophisticated and profound conditions that have to be managed for creating value.

INTRODUCTION

Idea generation or ideation is part of the early stages of new product development (NPD) also known as the "front-end" and supports product concept inception (Khurana and Rosenthal, 1998). The front-end is also named "fuzzy front-end" as these early stages lack "well-defined processes, reliable information and proven decision rules" (Dahl and Moreau, 2002). The analysis of NPD practices emerging from the PDMA best practices study indicated that "idea generation and management seem to be rather poorly managed in the FFE": a significant part of the ideas seems to have been generated by an informal process or without specific prompting (Barczak et al., 2009). These new ideas may have different sources, involving customers, other companies and employees (Cooper and Edgett, 2008).

Methods and techniques have been proposed and are used to improve the idea generation process (Smith, 1998, Cooper and Edgett, 2008). Among these techniques, bionics is described as an analogy strategy for generating ideas as users are asked to think about the way the problem is solved in nature (Smith, 1998). Although using nature for generating ideas is not new, its systematic application and the development of methodologies for it are relatively recent (Vincent et al., 2006, Marshall and Lozeva, 2009).

Literature use different terms to characterize the use of knowledge from nature to idea generation and product development: bionics, biomimetics, biomimicry, biologically inspired design or bioinspiration. One notion that these terms refer to is that engineering can copy or imitate (parts of) natural systems (bionics – like (ic), life (bio) – Shu et al., 2011; biomimetics, biomimicry – imitate (*mimesis*), life (*bios*) – Bar-Cohen, 2006, Benyus, 1997). The other notion is that (parts of) natural systems may serve as "mental stimuli" for generating an idea, as inspiration (biologically inspired, bioinspiration).

However, a clear distinction between imitation and inspiration from nature does not seem to be acknowledged and these terms are often considered as synonyms that can refer to both notions. For example, Vincent et al. (2006) consider these terms as synonymous implying "copying or adaptation or derivation from biology". Shu et al. (2011) also consider these terms as synonymous "to mean emulating natural models, systems, and processes to solve human problems". Benyus (1997), define biomimicry as "a new science that studies nature's models and then imitates or take inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf".

Other directions on the use of biological knowledge for product development, involve applying engineering knowledge to "solve problems in life sciences", for example, on the development of medical devices, sensors, implants, prosthesis, etc. (Shu et al., 2011), and using biological systems for human purposes, as in synthetic biology, where engineering knowledge reconfigures biological systems or create new ones (Schyfter, 2012) or in more common activities such as animal husbandry or agriculture. The direction that will be explored in this paper is the biological inspiration for idea generation.

Considering the importance of the idea generation to NPD (Amabile, 1996, Dahl and Moreau, 2002, Reid and de Brentani, 2004, Cooper and Edgett, 2008, Im et al., 2013), this paper aims to propose a model of the process of inspiration from natural systems during the fuzzy front end of NPD, that could reinforce the systematic use of bioinspiration for idea generation and its implementation in a company context for promoting innovative design.

The paper is organized as follows: the first section contains a brief literature review of the biologically inspired design. Next, the inspiration process of a sample of three selected case examples will be presented and analyzed using a framework based on the C-K design theory. A discussion on the findings of this modeling of inspiration will lead us to the conclusions about using biological inspiration in the context of innovative new product development and its managerial implications.

THEORETICAL BACKGROUND

In this section, a review of the main aspects of the literature on the bioinspiration process, including the definitions and methods described for integrating biological inspiration in product design and development will be presented. For commodity reasons, this literature review will not recall the state of the art of idea generation for NPD and will focus on the part of the literature that is linked to bioinspiration and is appropriate to define our research issues and findings.

Definitions of bioinspiration

The process of using nature as a source of inspiration for design has occurred throughout human history but its systematic study aiming at improving new product development is relatively recent. Terms such as bionics and biomimetics were coined only in the 1960s.

Bionics was coined by Jack Steele from the US Air Force to describe "the science of systems which have some function copied from nature, or which represent characteristics of natural systems or their analogues" (Vincent et al., 2006). ‘Biomimetics’ was coined by Otto Schimitt, a scientist in biophysics and bioengineering, in the title of a paper presented in 1969 at the Third International Biophysics Congress (*Some interesting and useful biomimetic transforms*) (Harkness, 2002). The definition of biomimetics first appeared in the Webster's dictionary in 1974 as:

"the study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones" (Vincent et al., 2006).

Another term, biomimicry, is also used to describe this process, and was popularized by the book of Janine Benyus (1997).

Speck and Speck (2008) distinguish seven subdivisions in biologically inspired research: architecture & design, lightweight construction & materials, surfaces & interfaces, fluid dynamics of swimming & flying, biomecatronics & robotics, communication & sensorics and optimization.

One of the most known examples of successful bioinspired design is Velcro, created in 1955 by the Swiss engineer George de Mestral after observing that the seeds of the burdock plant attached to his dog's fur or to fabric of his clothes. The observation of these seeds on the microscope showed that the hooks that stick from the seed attach to the fur or fabric, gripping instantly but ungripping with a light force. He used the "hook and loop" concept to create the Velcro zip fastener which has in one side stiff hooks as the burs and in the other side loops in the fabric (Bhushan, 2009).

Using natural phenomena during the design process do not imply the need of an identical mimic, as shown in the Velcro example. The transfer of the biological phenomena into a technical solution is “hardly ever a direct copy of the biological solution” (Martone et al., 2010) and represents a “reinvention inspired by nature” (Speck and Speck, 2008). Some reasons for getting inspired by nature for design include: minimal use of materials and energy, environmental friendliness, optimization of designs and process by natural selection and evolution (Reed et. al., 2009). For some authors nature’s solutions may seem inherently superior to human’s: “after 3.8 billion years of evolution, nature has learned: what works, what is appropriate, what lasts” (Benyus, 1997). Others consider that the differences from nature and technology transform nature in a useful source of inspiration for technology development (Vogel, 2003). However, as pointed out by Gonçalves et al. (2012), making use of sources of inspiration is not a guarantee for creative and successful outcomes of the design process.

Biologically inspired design

These innovations inspired by nature have stimulated attempts of systematization of the biologically inspired design processes. Vincent et al. indicated in 2006 that "no general approach has been developed for biomimetics".

From the analysis of the biomimetic design process as a whole (from the initial concept to product development), two directions were identified (Helms et al., 2009, Speck and Speck, 2008): the "*bottom-up*" approach (also named "solution driven" or "biology push") and the "*top-down*" approach (also named "problem driven" or "technology pull"). The steps of these two approaches are summarized in Table 1. Helms et al. (2009) observed that in real situations, these steps do not occur sequentially.

Bottom-up		Top-down	
Starting point	Fundamental research biologists	**Starting point**	An engineering problem
Detailing and principle extraction	Understanding biological model and identifying "principles"	**Search for analogies for the problem**	Search for analogies in biological knowledge
Abstraction	Transforming the biological principle in a "solution neutral form" and reframe the solution for engineers understanding	**Selection of the suitable principles**	Suitable principles of one or more biological models analyzed
Technical implementation	Product development using the biological principle extracted	**Abstraction**	Transforming the biological principle in a "solution neutral form" and reframe the solution for engineers
		Technical implementation	Product development using the biological principle extracted

Table 1 : Steps for top-down and bottom-up biomimetic approaches for NPD (Speck and Speck, 2008, Helms et al., 2009)

In the bottom-up approach, the starting point for the product development is the research of biological systems by biologists, which is further completed by a detailed understanding of the form-structure-function relationships and an identification of the principles discovered from the biological model. These principles are then abstracted for facilitating the comprehension by people without a strong biology background in order to guide their technological implementation (Speck and Speck, 2008, Masselter et al., 2011). Before technological implementation, Helms et al. (2009) include other steps to the bottom-up approach: problem search, in which a search for human problems for applying the biological principle takes place, and problem definition, where the identified problem is defined using functional decomposition (Shu et al., 2011).

The top-down approach starts with a definition of the problem to be solved in a way that allows the search for biological analogies. In this process there is also an abstraction step like the one described for the bottom-up process. The top-down process may also indicate some areas of biology where there may be some lack of fundamental data. This knowledge extension was called "extended top-down process" by Speck and Speck (2008). This extension of knowledge on biological phenomena may also result from a bottom-up process, which was named "integrative organism-driven biomimetic approach" (Hesselberg, 2007).

Considering these two approaches, biomimetic design appears as a case where designers have a problem and in order to solve it they decompose the problem, by analyzing its functional requirements and finally solutions from known designs (in the case of biomimetic design, from designs found in natural systems) are transferred to the current problem and the solution is thus incrementally developed (Vattam et al., 2010).

Besides, "bottom-up" and "top-down" definitions also have many points in common with the conceptual design phase of systematic design (Pahl and Beitz, 1984), such as identification of the functions and sub-functions and the search for solution principles in order to generate concepts (Sartori et al., 2010). Biological phenomena, abstracted in its essential functions would act as a source of inspiration for the solution principles (Nagel et al., 2010). A broader definition of the role of biological phenomena in the conceptual design step of systematic design is as analogies in the idea generation process for the solutions search (Mak and Shu, 2008, Wilson et al., 2010, Vattam et al., 2010), meaning that a "transfer" of elements from the biological world to the domain of the object being designed takes place.

In biology, analogy is defined as "a resemblance between two features that is due to convergent evolution rather than to common ancestry" (Sadava et al., 2011). For engineering design, Christensen and Schunn (2007) identified three functions for analogies: explanation, problem-solving and problem identification. For the problem-solving process, analogies are used as a means that allow the problem solver to "access, map, and transfer knowledge situated within an analogous situation" (Kalogeratis et al., 2010). Considering the idea generation process, analogies have been considered as a technique for idea generation (Smith, 1998). "Analogical inspiration" is considered as a way of increasing the number and the variety of solutions to a problem that can lead to more "novel" designs (Tseng et al., 2008).

Some experimental studies have indicated that the use distant analogies, i.e. the source and the target domains belong to different sectors could be "positively related to originality in design" (Dahl and Moreau, 2002). The effect of the biological examples (distant analogies) in idea generation during conceptual design was the object of a cognitive study (Wilson et al., 2010) which indicated that biological examples indeed increased novelty although not significantly changing the variety of the ideas generated, when compared to a situation with no examples. Using human-engineered examples in the idea generation process had a similar effect on the novelty increase, but the variety decreased, which means that in a way exposure to the human-engineered examples leads to a greater fixation effect than biological examples.

Other studies on the analogy-making process that takes place during biomimetic design support the idea that nature is not a simple model for copy, but can be used as a "source of inspiration"(Mak and Shu, 2008, Helms et al., 2009, Vattam et al., 2010 and Sartori et al., 2010).

Methods to support biologically inspired design

Shu et al. (2011) identified two directions for the research on methods to support biologically inspired design: the first one related with the "search, retrieval and representation of the biological phenomena for design" and the second one related with "better understanding and support the application of biological analogies to design". The references and methods associated with these two directions are summarized in Table 2.

The first direction, related to the search, retrieval and representation of biological phenomena for design, include methods such as the integration of biologists in the design process, as proposed by the "Biologists at the Design Table" scheme (Peters, 2011), or the development of databases that contain biological phenomena.

One online accessible database is the AskNature database, a project of the Biomimicry Institute, which has a structure composed of group functions, sub-groups and functions. Queries for searching the database are formulated using the question “How would nature….?” (e.g. “How would nature control temperature?”). There is also the possibility of searching by the biological phenomena or living system, e.g. “photosynthesis”, “lotus leaf”.

“Search, retrieval and representation of the biological phenomena for design”	**“Better understanding and support for the application of biological analogies for design”**
Ask biologists directly	Compound Analogies, DANE (Design by Analogy to Nature Engine) (Helms et al., 2009, Vattam et al., 2010, Wiltgen et al., 2011)
Use of database asknature.org (The Biomimicry Institute)	Support « transfer » in biomimetic design and functional representation for aiding biomimetic and artificial inspiration (Sartori et al., 2010, Chakrabarti et al., 2005)
Natural-language approach (Shu, 2010)	Function-based, biologically inspired concept generation (Nagel et al., 2010)
Bio-TRIZ (Vincent et al., 2006)	
Law of system completeness and Substance-field analysis applied to biological systems (Helfman Cohen et al., 2011, 2012)	

Table 2 : Research directions on methods to support biomimetic design (adapted from Shu et al., 2011).

Databases are dependent on the amount of information entered on it and sometimes the keywords used for queries may be misleading (Shu et al., 2011). In order to attenuate this limitation, another approach that use keyword search on texts written on natural-language format, e.g. biology books, scientific communications and papers, was developed (Shu, 2010). Difficulties for the application of this method reside on management of the quantity and the quality of the matches and on the fixation effects that biological examples may induce in designers (Shu et al, 2011, Mak and Shu, 2008).

TRIZ tools have also been used for facilitating the comprehension of biological systems by engineers and the problem-solving activity. The Bio-TRIZ approach (Vincent et al., 2006) proposes a new contradiction matrix based on biological phenomena as a way of stimulating the transfer between biology and engineering. Hill (2005) uses TRIZ for framing the problem and uses catalogue sheets of biological systems basic functions for identifying similarities between biological structures and the contradictions to be solved. Helfman Cohen et al. (2011,2012) uses other TRIZ tools such as “the law of system completeness” and the “substance-field analysis” for acquiring a better understanding of biological systems thus facilitating the transfer for the engineering world.

The second direction, related to supporting the application of biological analogies for design, has studies on the cognitive process of biologically inspired design (Helms et al., 2009, Vattam et al., 2010) understanding the conditions for use and contents of analogies during the whole design process (including the idea generation). Other studies have focused on the transfer process during biomimetic design process, using tools such as the IDEA-Inspire software to facilitate the use of biologically inspiration for idea generation (Chakrabarti et al.,2005) and the SAPPHIRE model for understanding biological systems (Sartori et al., 2010). This last study could also be included on the first direction. The model developed by Nagel et al.(2010), include representing the biological systems using functional models for facilitating the transfer between biology and engineering, but it depends on the database of biological phenomena and on the designer's skills.

Conclusions from the theoretical background

This literature review on biomimetic design showed the main research directions in the field. Many authors recognize that identical mimicking of natural systems is very unlikely, and that nature should be seen as a source of inspiration (Vogel, 2003, Speck and Speck, 2008, Martone et al, 2010). Considering the whole biomimetic design process, two directions were identified: top-down and bottom-up. In the first one, an engineering problem triggers the quest for biological solutions that could be helpful for solving the problem, in the second one, the study of biological phenomena reveals some interesting property that could be useful for technical applications. In both cases, inspiration from nature is seen as a transfer between biology and engineering domains for generating ideas. Another research direction is on methods that support biologically inspired design, that aim to ease the search and retrieval of biological phenomena that could be relevant for solving a design problem and also to facilitate the use of biological analogies in design. The content of the transfer from the biological phenomena and the process for retrieving "inspiring" biological phenomena have also been studied in literature for helping in the integration of biological inspiration to the design process.

RESEARCH METHODOLOGY

These studies, although representing a first step for systematizing biomimetic design method, do not fully explain the reasons for "inspiration searching" in biological knowledge bases. Based on this conclusion, our main research question was formulated:

RQ : What means using inspiration from nature for new product development?

In order to access the meaning of bioinspiration for the process of new product development, two subsidiary research questions were also formulated: *RQ1: Why seek inspiration in nature?* and *RQ2: How does bioinspiration work?*

Three case examples, supported by scientific publications accounting for the detailed bioinspiration processes, were chosen from the literature to explore this research question.

The core basis for the search of bioinspiration examples in literature were the journal Bioinspiration and Biomimetics (IOP publishing), as it contains bioinspired work from different fields of research (robotics, materials, architecture, construction, etc.) and is the journal publishing the greatest numbers of papers on biomimetics per year (Lepora et al., 2013), the review on biomimetics edited by Y. Bar-Cohen (Bar-Cohen, 2012), which has a chapter dedicated to biomimetic products (Masselter et al., 2012) and the review of biomimetic examples by Bhushan (2009).

In the field of new product development, references that cite or make connections to bioinspiration applied to NPD are not numerous. This conclusion came from a search using keywords related to bioinspiration (biomimetics, biomimicry, bionics and biologically inspired) in all issues (until 2013) of two journals on the NPD field: the Journal of Product Innovation Management and the Creativity and Innovation

Management Journal. These results are summarized on Table 3. In the Creativity and Innovation Management Journal, most of the references cite the use of bionics or biomimetics coupled with TRIZ (Hill, 2005, Moerhle, 2005, 2010, Vincent et al., 2005). Buijs et al. (2009) describe a case of a real-life technical problem using creative problem solving techniques, and used nature for generating analogies to the problem in the phase of idea generation. Hauschildt (1996) cites bionics as a creativity technique.

Search term	Journal of Product Innovation Management	Creativity and Innovation Management Journal
Bioinspir*	No matches	No matches
“Biologically inspired”	No matches	No matches
Biomim*	Kalogeratis et al., 2010	Vincent et al.,2005 Buijs et al., 2009
Bionic	Kalogeratis et al., 2010	van Andel, 1992 ; Hauschildt,1996 Hill, 2005; Vincent et al., 2005 Moehrle,2005, 2010

Table 3 : Search results using keywords related to bioinspiration in two NPD journals: Journal of Product Innovation and Management and Creativity and Innovation Management Journal

The theoretical framework used to model inspiration from nature in this paper is based on the C-K design theory. We chose a design theory for this modeling as it captures the specificity of the design reasoning (Hatchuel et al., 2012). Design theories have been applied as theoretical frameworks for explaining fixation effects (Agogué et al., 2011, Hatchuel et al., 2011), for extending the scope of creative conceptual design (Shai et al., 2009), for discussing the process of creative concept generation in design (Taura and Nagai, 2013).

C-K theory was chosen among other design theories such as the General Design Theory (GDT), the Axiomatic Design (AD), the Coupled Design Process (CDP) or the Infused Design (ID). This choice relates to the fact that C-K theory “attempts to improve our understanding of innovative design”, allowing the modeling of the generation of new objects (Hatchuel et al., 2012) and also gives knowledge a wider variety of roles in the design process, not only restricting it to being a space of solutions. The analytical power of the C-K theory for the innovative design has been confirmed by existing literature (Reich et al., 2012, Sharif Ullah et al., 2012). Moreover, C-K theory has been used to model creativity process in industrial R&D (see Hatchuel et al., 2012 for examples).

C-K theory: notions and operations

The C-K theory was introduced in 2003 by Hatchuel and Weil. In this theory, design is defined as “an interplay between two interdependent spaces”, the space of concepts (C) and the space of knowledge (K). Space K contains the available knowledge. Space C contains propositions, called concepts, that are “neither true nor false in K about partially unknown objects x”. Design proceeds by the expansion of this initial concept into other concepts (by partitioning the concept) and/or into new knowledge. In this way, in C-K theory, both C and K spaces are expandable and these transformations between spaces and inside the same space are called “operators”. There are four operators in C-K theory: C→C, C→K, K→K and K→C. The design solution, is the “the first concept to become a true proposition in K” (a conjunction).

These two spaces have different structures. As in C-space only partitioning or inclusion are allowed, this space has a tree structure, in which each node represent a partition in several sub-concepts (Hatchuel and Weil, 2003). The K space grows like “an archipelago”: new propositions are added without necessarily following a stable order or being connected directly (Hatchuel et al., 2009). Figure 1, summarizes the operators and the main features of the C-K theory.

The theory proposes two types of partitioning for concepts: *restrictive partitions* and *expanding partitions* (Hatchuel and Weil, 2003). The restrictive partitions add a property to a concept already known as a property of the entities concerned. The expanding partitions add properties not known in K as a property of the entities concerned. Therefore, "creativity and innovation are due to expanding partitions of concepts".

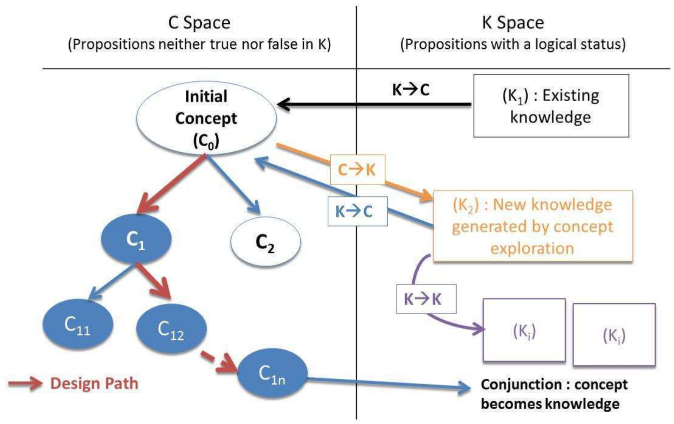

Figure 1 : C-K diagram and operators (adapted from Hatchuel et al., 2003, 2009, 2012)

MODELING BIOINSPIRATION FROM CASE EXAMPLES

For the study of the bioinspiration process, we have detailed three examples, which are described in biomimetic literature. Two of them were subject of articles of the journal Bioinspiration and Biomimetics (Lienhard et al., 2011 – Flectofin®, Solga et al., 2007 – the lotus effect). The third one was cited by Bhushan (2009) on its review on biomimetics and is the object of a great number of publications in the biomimetic field.

Self-cleaning surfaces inspired by the lotus-effect

During their works on the study of leaf surfaces by scanning electron microscopy (SEM), Barthlott and Neinhuis (1997) observed that cleaning the leaves before examination was always necessary for “plants with smooth leaves surfaces” while those with “epicuticular wax crystals were almost completely free of contamination”. These epicuticular wax crystals were well known for conferring water repellency. Moreover, studies on the relationship between particle deposition and surface roughness had already been made. These authors observed that the idea of a correlation between water repellency and reduced contamination already existed, but lacked experimental data for consolidation.

Barthlott and Neinhuis used the observation of the lotus leaves to elaborate a model explaining the relationship between surface roughness, particle removal (self-cleanliness) and wettability (Barthlott and Neinhuis, 1997). In particular, the result of this work was patented for application in human-made surfaces (Barthlott, 1998, Barthlott and Neinhuis, 2000). The surfaces were rendered self-cleaning and hydrophobic by having a structure of elevations and depressions made of hydrophobic polymers or materials.

The Lotus-effect mechanism was used for the development of exterior coatings such as *Lotusan*® (Sto Corp.), used for façade protection (Bhushan, 2009). It has also been introduced in fabrics by immobilizing hydrophobic silica particles functionalized with vinyl groups using UV photo-grafting over a poly lactic acid (PLA) fabric. In the process a rough surface with superhydrophobicity is created, thanks to the silica particles and the vinyl groups (Singh et al., 2012).

Considering the two biomimetic approaches described in the theoretical background of this paper, the products developed based on the Lotus-effect were the result of a bottom-up approach, in which the biological phenomena triggered the search for potential technological applications. Seen from a C-K perspective, the first studies of Barthlott and colleagues on leaf surfaces formed a knowledge base on these biological structures. The observation of an interesting property during the construction of this knowledge base, the non-contamination of the leaves with epicuticular wax crystals led to the formulation of an expanding partition for the concept of self-cleaning surfaces: "with a rough surface" (opposed to rendering smooth surfaces self-cleaning). The study of the lotus model, activated the traditional knowledge base on the "behavior of liquids applied to solid surfaces" and allowed to explain the reasons for obtaining the lotus effect: rough surfaces with hydrophobic coatings. The products with the lotus-effect were then developed using systematic engineering design (embodiment design, detail design): façade paints with nanostructured materials (Lotusan®), fabrics, etc. This process is schematically represented in Figure 2.

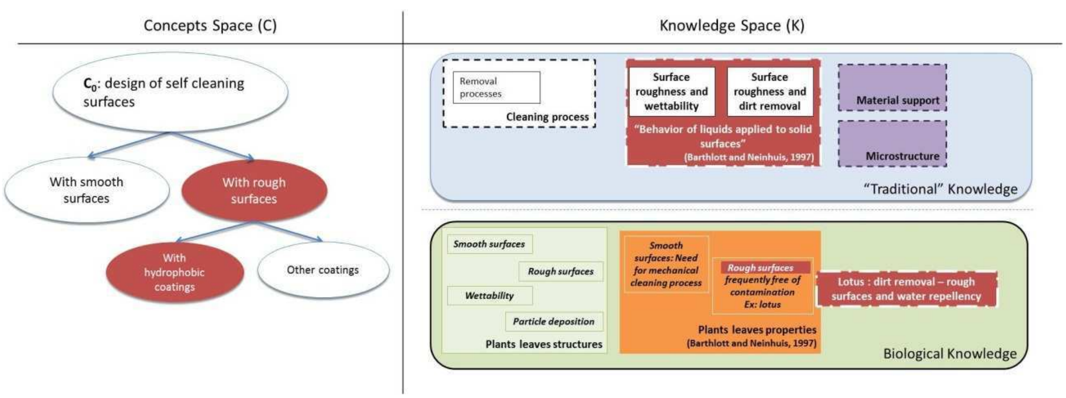

Figure 2 : C-K diagram on self-cleaning surfaces (inspired by the lotus leaves)

Development of a hingeless flapping mechanism inspired by the bird-of-paradise

Reducing the complexity of movable building structures, such as façade shading systems is a challenge for architecture (Knippers and Speck, 2012). The technical hinges used in blinds and umbrellas for deployability are subjected to constant load cycles that wear the mechanical pieces and cause the need of constant maintenance (Lienhard et al., 2011). Noting that among plants there are hinge-free movements and reversible deformation principles, an "interdisciplinary research collaboration" between architects, engineers and biologists from the Institute of Building Structures and Structural Design (IKTE) of the University of Stuttgart and the Plants Biomechanic Group of the University of Freiburg began to investigate how these plants could be used for developing technical applications (Masselter et al., 2012).

During this research, a screening process on plant movements led to the identification of a kinematic principle for a façade shading system. This principle was found on the perch of the ‘bird of paradise’ (*Strelitzia reginae*) flower. This perch remains closed by its two adnate petals protecting the flower’s reproductive organs. Birds wishing for the nectar of the flower land on the perch, bending it down. This bending simultaneously unfolds the petals allowing pollen to touch the bird, ensuring pollination (Knippers and Speck, 2012).

Biologists investigated further this mechanism and the flower structure. A physical model that had a similar behavior was built, by attaching perpendicularly a thin shell element – the fin – to a rib – the backbone. Bending the rib causes a bending motion of the shell by “torsional buckling”. The Strelitzia reginae mechanism was the element that showed how using this torsional buckling was possible, as buckling is usually considered as a material failure mode. In the next steps, studies on possible configurations of the rib-shell element were carried over, and some adaptations of the observed principle to the physical structure were made: stiffness adaptations, stress reduction and materials choice (Lienhard et al., 2011). The result of this development process was a patented façade shading system called *Flectofin*® (Schleicher et al., 2011).

Seen using a C-K perspective, summarized in Figure 3, the existing knowledge about deployable systems in architecture, using hinges and rollers have triggered the generation of the initial concept for architects. The search for alternatives to these systems led the group to the activation of the biological knowledge on plants movements, which had an unexpected property: some plants had deployable mechanisms without hinges. This generated an expanding partition to the initial concept: “without using hinges”.

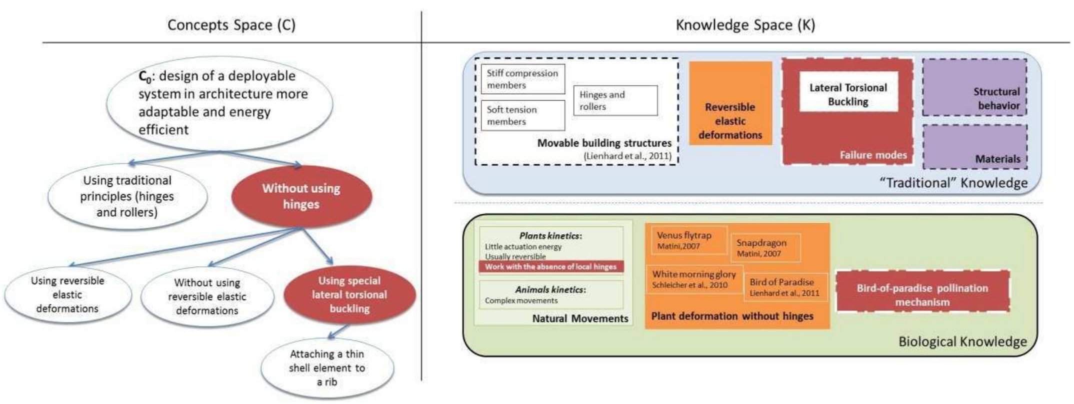

Figure 3 : C-K diagram on deployable systems in architecture (inspired by plants kinetics)

The search for new attributes to this concept, led to the expansion of the knowledge on plant deformation avoiding hinges. Several mechanisms were studied, i.e. they were interpreted considering existing knowledge, using for example 2D or 3D models (Matini and Knippers (2008) called these models “abstract formal patterns”). The main knowledge base activated was about reversible elastic deformations of materials. During this study on the reversible deformation mechanisms of plants, the pollination mechanism of the bird of paradise was identified as being a “special form of lateral torsional buckling” (Lienhard et al., 2011). This knowledge, referred to a known knowledge base about a material deformation process, but it revised the traditional way of perceiving this knowledge, changing from a failure mode to a desirable property.

The concept “without using hinges”, could then be partitioned into: using the special form of lateral torsional buckling, that led to expansions on the traditional knowledge bases, to conceive and test a physical model that would have the special form of lateral torsional buckling. This physical model was obtained using “a thin shell element attached orthogonally to a rib or beam element” (Lienhard et al., 2011). The next steps correspond to traditional engineering steps, where the possible structural configurations and the structural behavior were modeled and tested, the materials chosen, etc.

Development of gecko-inspired adhesives

The most common man-made adhesives use wet adhesives for the attachment of two surfaces (Bhushan, 2009). Geckos have “strong, high repeatable, high speed and controllable attachment and detachment capabilities on a wide range of smooth and slightly rough surfaces” (Mengüc et al., 2012), which had already been observed by Aristotle two millennia ago (Autumn and Peattie, 2002).

These controlled adhesive properties of geckos, unmatched by human-made adhesives, stimulated researches to explain the “secret of geckos’ adhesive capabilities” (Autumn and Peattie, 2002). Some hypothesis for the gecko’s attachment included suction, friction or intermolecular forces (Autumn et al., 2000). These authors revealed that the attachment properties of gecko were linked to van der Waals forces (intermolecular forces) between setae (keratinous hairs covering gecko’s toes) and the surface and that the gecko’s toe uncurling and peeling movements also contributed to the adhesive properties of setae.

This knowledge about the adhesion properties of geckos has stimulated research on gecko-inspired adhesives. One direction of these researches aims at fabricating micro and nanostructured fibrillar surfaces (e.g. the review of fabrication approaches of gecko-inspired surfaces by Boesel et al. (2010)) that could have reversible dry-adhesion properties (Bhushan, 2009). Applications of these adhesives include clean transportation during the assembly process and biomedical skin patches (Kwak et al., 2011). On the other hand, Bartlett et al. (2012) indicate that these attempts have poor adhesive properties at large length scales, and used the knowledge acquired with the studies on gecko’s adhesion to develop a scaling theory that allowed the development of “reversible, hand-sized synthetic adhesive structures with unprecedented capacity, even without fibrillar features”.

Using C-K theory for analyzing this case, (Figure 4), the starting point was the biological knowledge about the gecko, which had interesting abilities: “climb rapidly up smooth vertical surfaces” (Autumn et al., 2000), or “even upside down” (Autumn and Peattie, 2002). The initial concept could be interpreted as the “design surfaces with strong and controllable adhesive properties”. This stimulated a deeper research for understanding the gecko’s adhesion. This research represent an expansion of the biological knowledge about gecko's adhesion and activated traditional knowledge bases on the mechanisms for adhesion, such as suction, friction and intermolecular forces. The measurements by Autumn et al. (2000) showed that the adhesion mechanism was linked to the setae and the van der Waals forces. This allowed the partitioning of the initial concept on “using fibrillar structures in the surface”, which led to the development of fabrication techniques and surfaces using this kind of surface pattern for adhesion. The other partition of this concept could then be formulated as: “without using fibrillar structures”.

As these artificial fibrillar structures were not adaptable to larger scales, Bartlett et al. (2012) developed a “scaling theory”, which used the knowledge about the energy balance of a material adhering through a given surface area, and led to the development of unpatterned surfaces with reversible controllable adhesive properties, which represent a partitioning of the concept “without using fibrillar structures”.

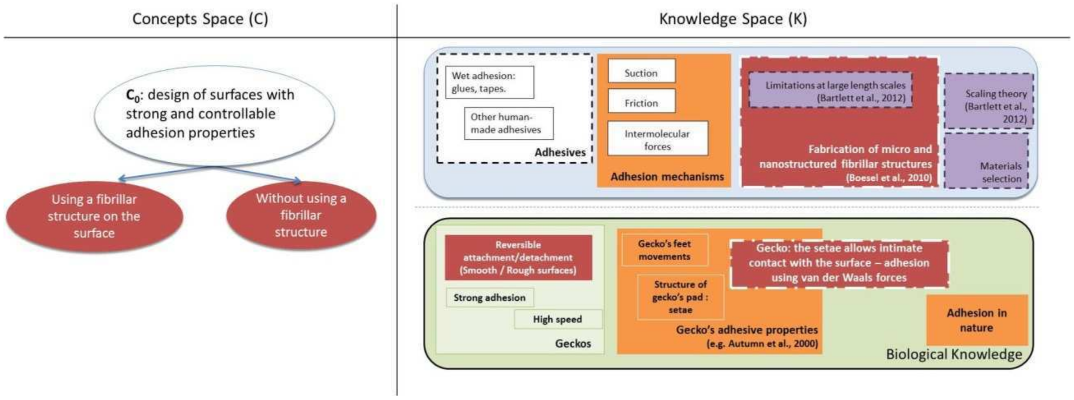

Figure 4 : C-K diagram for gecko inspired adhesives

DISCUSSION

Bioinspiration modeling using C-K theory

These three examples use bioinspiration for product development. The outcome of each case is a bioinspired product *with little or no similarity* with the biological inspiration, in terms of forms, materials or processes.

In the lotus and the gecko case, the observation of natural phenomena is at the origin of the process of new product development. The biological knowledge triggered the identification of an interesting property for product development: self-cleaning using surface properties (lotus) and dry and controllable adhesion (gecko). The Flectofin® case started with a design problem, and using biological knowledge allowed the development of an innovative technical solution for façade shading systems.

Also in the Flectofin® case, the deformation of the bird-of-paradise flower perch had to be explained using traditional knowledge about lateral-torsional buckling. This knowledge was not unknown to architects, but was considered undesirable as it is a material failure mode. This property (the “special form of lateral-torsional buckling”) allowed the development of the mechanism for the façade system. The product was further developed using traditional knowledge on materials, structural systems and behavior. The Lotus self-cleaning and the gecko’s adhesion properties have expanded traditional knowledge for explaining these phenomena. In the lotus-case, the exposure of rough leaves to particles and humidity generated the concept of “self-cleaning surfaces with rough surfaces” and also stimulated the use of already existing knowledge bases on the “behavior of liquids applied to solid surfaces” and on the relationship between roughness and particle removal. In the gecko’s case, the knowledge about the van der Waals adhesion using fibrillar structures was applied for the design of fibrillar adhesives and also allowed the development of the other partition, for the design of unpatterned adhesive surfaces. In these three cases, there is a property that allows the partitioning of the initial concept that is used for further product development within the traditional knowledge.

The modeling of each case of bioinspiration using the C-K design theory gives some insights about the role of bioinspiration in the design process. Figure 5 summarizes the following steps using a C-K diagram:

<u>Step 1</u>: Biological knowledge is activated when traditional design paths seem to be blocked, or it helps formulating a new initial concept.

Step 2: Expanding the knowledge on biological systems (screening different systems, explaining phenomena) will indicate whether the traditional knowledge for understanding these phenomena:

i) Already belongs to designers;
ii) Must come from another domain;
iii) Is completely unknown and will need other types of knowledge expansions.

In all these three possibilities properties that oblige reviewing the traditional knowledge, using *non-spontaneously* activated knowledge will be identified.

Step 3: These unexpected properties allow the partitioning of concepts and indicate the paths for bioinspired design.

Step 4: This process will continue using elements from the traditional knowledge space for product development.

This allows us to answer the research questions of this study. Seeking inspiration in nature occurs when traditional design paths seem to be blocked (*RQ1: Why seek inspiration in nature?)*. Bioinspiration uses unexpected properties that may be found in biological knowledge for generating new concepts and revising the traditional knowledge bases. *(RQ2: How does bioinspiration work?)*

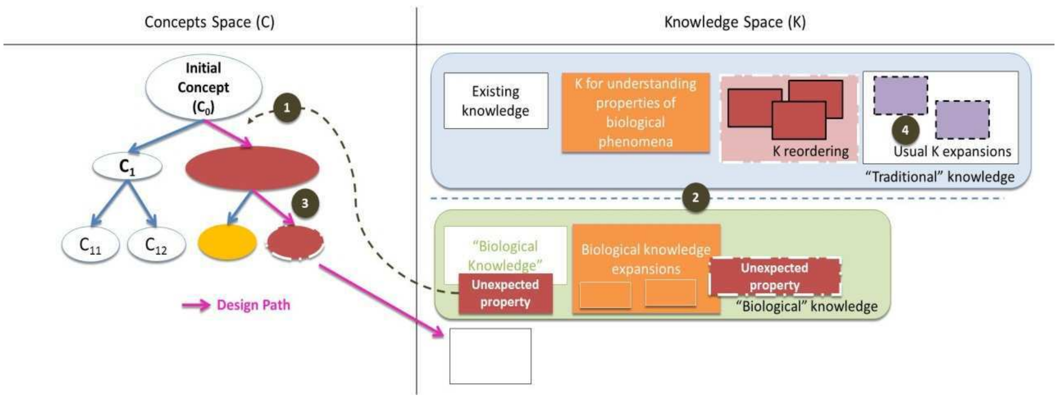

Figure 5: C-K diagram for bioinspiration

This interpretation of the process of bioinspiration is complementary to the analogy making process and the top-down and bottom-up approaches, described in literature. It indicates that using biological knowledge for idea generation is useful when it allows the partitioning of concepts in unexpected ways, considering the traditional knowledge available to designers. The biological knowledge is then a trigger for concept partitioning and traditional knowledge activation which will allow subsequent product development.

Implications for management

The use of biological knowledge bases for generating the new concepts has consequences on knowledge management and design organization.

Biological knowledge must be systematically gathered for allowing the identification of as many different interesting partitions as possible; this knowledge gathering may need the use of databases for systematically identifying interesting biological phenomena or the contact with biologists. A difficulty associated with this task is the identification of the suitable domains of biological knowledge and of the interesting properties, because of differences of vocabulary and communication issues of designers and biologists.

This exploration of the biological knowledge also triggers reorganization and reconstruction of the traditional knowledge bases: new competences and a revision of the traditional knowledge are required to further develop the bioinspired concepts.

Other important managerial implication highlighted by the bioinspiration modeling using C-K theory is that bioinspiration and traditional product development methods are complementary and not contradictory: bioinspiration activates a “new” knowledge base that aid on the process of identifying unexpected properties considering the traditional knowledge and indicates directions for further knowledge acquisition and revision. Nevertheless, traditional knowledge for further development remains necessary. The subsequent steps of product development are exactly the same of a new product using only traditional knowledge for the development.

Experimental observations of the bioinspiration process are taking place at a large French automaker company, Renault SAS. In 2011, a project for generating new concepts for improving the environmental footprint of cars was launched. Consultations with senior experts, knowledge about ongoing projects were used for elaborating a C-K diagram. Some paths seemed to be “blocked” and a research about the possibility of using biological knowledge for “unblocking” and these paths started. This ongoing research has encountered some of the difficulties mentioned before (choosing the biological knowledge bases for each case, contacting biologists, traditional knowledge revision). The C-K modeling for bioinspiration and its managerial implications presented in this paper will provide the referential for analyzing the creative power of bioinspiration in NPD for this ongoing project.

CONCLUDING REMARKS AND MANAGERIAL IMPLICATIONS

From the analysis of three case studies on bioinspired products using C-K theory, some new insights about the inspiration process were obtained. Firstly, the biological knowledge is used in the design process when traditional design paths seem to be blocked. The bioinspiration process consists in using the biological knowledge for adding properties to initial concept and expanding and reorganizing the traditional knowledge bases. These properties can be different from the traditional knowledge properties, because natural systems are distant from human-engineered systems (materials used, hierarchical organization, survival conditions) and also because they can activate different knowledge bases for explaining a phenomena.

The C-K modeling for the bioinspiration process showed that applying biological inspiration requires the acquisition of the biological knowledge in order to find "unexpected properties" that will reorganize and expand knowledge. The first attempt of using the model of bioinspiration proposed in this paper in a large automaker company showed that one of the greatest difficulties for a systematic implementation of bioinspiration in the FFE is finding the suitable biological knowledge bases. Methods such as the one proposed by Helfman-Cohen et al. (2011,2012) could help on the systematization of the biological systems facilitating this retrieval process.

Regarding the managerial implications of this bioinspiration modeling, the C-K framework structures the relationship between traditional knowledge and biological knowledge. It also clarifies the process of generating and partitioning of concepts using biological knowledge. This spurs new forms of knowledge management and design organization. By making explicit the role of the biological knowledge, the risks of “over-idolization” of nature pointed out by Kaplinsky (2006) and Volstad and Boks (2012), are considerably reduced.

The next steps of this research include implementing the C-K modeling for bioinspiration on the project of the generation of new concepts for reducing environmental footprint at Renault SAS and analyzing its managerial implications. Further research should generalize our findings to any inspirational logic in the design process, even if it does not have biomimetic aspects.

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